Regional Information Report 3A.17-02

2016 Kuskokwim River Chinook salmon run reconstruction and 2017 forecast

by

Zachary W. Liller

April 2017

Alaska Department of Fish and Game **Division of Commercial Fisheries**

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, and Special Publications. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	$log_{2,}$ etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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by
Zachary W. Liller
Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage

Alaska Department of Fish and Game
Division of Commercial Fisheries
333 Raspberry Road, Anchorage, Alaska, 99518-1565

April 2017

Zachary W. Liller
Alaska Department of Fish and Game, Division of Commercial Fisheries,
333 Raspberry Road, Anchorage, AK 99518, USA

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ABSTRACT

A maximum likelihood model was used to estimate the 2016 drainagewide run size and escapement of Kuskokwim River Chinook salmon (*Oncorhynchus tshawytscha*). Total run and escapement were estimated to be 176,916 (95% CI: 134,407–232,871) and 145,718 (95% CI: 103,209–201,673) fish, respectively. Model estimates were informed by direct observations of the 2016 escapement at 15 locations (5 weirs and 10 aerial surveys), combined with historical observations of escapement, harvest, and mark–recapture data dating back to 1976. There is considerable uncertainty in the 2016 model estimates. However, model results are adequate for drawing broad conclusions about the 2016 run and escapement. The total run of Chinook salmon in 2016 was the largest since 2009, but considerably less than long-term average abundance. Total escapement was near average due to conservative management and harvest restrictions throughout the run. The drainagewide sustainable escapement goal of 65,000–120,000 was probably exceeded in 2016.

Key words Chinook salmon *Oncorhynchus tshawytscha*, run reconstruction model, escapement, Kuskokwim River.

INTRODUCTION

This report describes methods used to estimate the 2016 drainagewide run size and escapement of Chinook salmon (*Oncorhynchus tshawytscha*) returning to the Kuskokwim River in western Alaska. Because it is not possible to count all Chinook salmon that return to the Kuskokwim River, estimates of annual abundance and escapement were made using a maximum likelihood model. The model (Bue et al. 2012), with subsequent revisions (Hamazaki and Liller 2015), is an extension of the approach presented by Shotwell and Adkison (2004) and was specifically developed for use in data-limited situations. The model combines information on subsistence harvest, commercial catch and effort, sport harvest, test fish harvest and catch per unit of effort at Bethel, mark–recapture estimates of inriver abundance, counts of salmon at 6 weirs, and peak aerial counts from 14 tributaries spread throughout the Kuskokwim River drainage (Figures 1 and 2). Each of these data sources provides an index of total abundance and some data are more informative than others. The model provides an approach to combine and weight available information about Kuskokwim River Chinook salmon abundance to arrive at a scientifically defensible estimate of total run size and escapement. Estimates produced by the model represent the most likely run size given the observed data.

The run reconstruction model was published in 2012 (Bue et al. 2012), and has quickly become an important tool to guide sustainable management of Kuskokwim River Chinook salmon fisheries. Model results contributed to a spawner-recruit analysis used to establish a drainagewide escapement goal of 65,000–120,000 for Kuskokwim River Chinook salmon (Hamazaki et al. 2012). The run reconstruction model has been used annually since 2013 as a postseason tool to determine if the drainagewide escapement goal was achieved. Proper application of the escapement goal requires that the model structure not change substantially relative to the model structure used to develop the escapement goal. Model results have also been used since 2012 to inform preseason management strategies for achieving escapement goals. Since 2014, a forecast range has been based on the prior year run size, and uncertainty in the forecast is calculated as the recent 7-year average percent deviation between subsequent year run sizes. The rationale for this approach is based on the observation of strong serial correlation between successive years of total run size.

The run reconstruction model requires regular review and, when necessary, updates to ensure unbiased estimation of total run and escapement. Both internal and external reviews have been conducted and others are ongoing. ADF&G (Alaska Department of Fish and Game) has encouraged and facilitated external reviews by providing fishery and assessment orientations, filling data requests, and providing model codes.

Catalano et al. (2016) provides a detailed 5 chapter document that highlights important investigations related to the run reconstruction model and subsequent stock recruitment analyses. The Auburn University research team concluded that the Kuskokwim River run reconstruction model was generally consistent with broadly accepted stock assessment modeling approaches and performed reasonably well in a series of simulation studies. They also demonstrated that ADF&G's sequential approach to incorporating the model estimates of total run size into a subsequent age-structured Byesian state-space spawner-recuit analysis produced similar estimates of population dynamics parameters and management reference points compared to an alternative approach where both models were integrated. Catalano et al. (2016) did identify some weaknesses in the current run reconstruction model. In particular, the approach used to weight input data resulted in an extreme and undesirable tendency to perfectly fit a single index project's time series in some years.

The Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI) has commissioned an independent peer review of the Kuskokwim Chinook Salmon run reconstruction model. That review is ongoing and we anticipate a final report in late 2017, followed by 2 collaborative modeling sessions in early 2018. The results of this independent review will be considered by ADF&G as we work with interagency partners to advance the run reconstruction model for future years.

ADF&G has also initiated a 2-step process to review and update the Chinook salmon run reconstruction model. The first step involved a 3 year effort (2014–2016) to estimate total run size using mark–recapture methods as a means to ground truth model results during years of low run abundance[1] (Liller 2013). The second step involved convening a Kuskokwim River Interagency Model Development Team (KRIMDT) to consider options for incorporating new abundance data and pending recommendations from the AYKSSI independent review panel. The KRIMDT consists of representatives from ADF&G, U.S. Fish and Wildlife Service Office of Subsistence Management, Bechtol Research, and Auburn University. The KRIMDT is charged with the following: 1) develop a model or set of candidate models capable of estimating run size, escapement, and productivity of Kuskokwim River Chinook salmon; 2) co-author a report detailing the development process, preferred model(s), and results of sensitivity or simulation analyses, data inputs, and model code; and 3) engage agency and public stakeholders in the model development process. The timeline for KRIMDT has not been constrained, but we hope to have results available in time for the 2019 Alaska Board of Fisheries meeting addressing the Kuskokwim Area.

Until such time that all ongoing model reviews and updates are completed, the published run reconstruction model remains the most appropriate tool for evaluating total run and escapement. The methods used in 2016 are based on those presented by Bue et al. 2012 and subsequent updates by Hamazaki and Liller 2015. The 2016 estimates extend the historical time series which

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[1] Mark–recapture studies *Inriver abundance of Kuskokwim River Chinook salmon, 2014* and *Inriver abundance and migration characteristics of Kuskokwim River Chinook salmon, 2015* will be available to the public in May 2017. The third study, *Inriver abundance and migration characteristics of Kuskokwim River Chinook salmon, 2016* is a preliminary draft and requires formal biometric and peer review. Final and preliminary results have been made available to the AYKSSI independent review team and the Kuskokwim River Interagency Model Development Team. All 3 studies are on file with the Kuskokwim Research Group, ADF&G Division of Commercial Fisheries, Anchorage. Hereafter cited as ADF&G *Unpublished*.

formed the basis for the drainagewide sustainable escapement goal for Kuskokwim River Chinook salmon.

OBJECTIVE

Estimate the total run size and escapement of Kuskokwim River Chinook salmon in 2016.

METHODS

MODEL OVERVIEW

Drainagewide escapement (E_y) of Kuskokwim River Chinook salmon for year (y) is equal to the drainagewide run size (N_y) minus harvest (C_y),

$$E_y = N_y - C_y, \tag{1}$$

where C_y is the sum of harvest by subsistence, commercial, sport, and test fisheries. Each part of Equation 1 is known to different degrees. Total annual escapement is indexed by count data from weirs and aerial surveys located throughout the lower, middle, and upper portions of the Kuskokwim River. Estimates of total abundance for scaling the model are available for 5 years, 2003 to 2007 (Schaberg et al. 2012). Direct estimates from Schaberg et al. (2012) were derived from a combination of mark–recapture data, escapement estimates, extrapolation of escapement values to unmonitored areas, and harvests. Total annual harvests are known with a high degree of confidence from commercial fish tickets and test fisheries. Subsistence harvest was estimated from extensive postseason surveys and the estimates are incorporated into the model without error. Estimates of sport fish harvest are less precise, but the effect of a lower level of precision is negligible given the small annual sport harvest.

Total run and escapement of Kuskokwim River Chinook salmon was estimated using a maximum likelihood model developed for data limited situations (Bue et al. 2012), with subsequent revisions (Hamazaki and Liller 2015) to the model configuration (summarized in Liller and Hamazaki 2016). The model simultaneously combined abundance data from multiple sources to estimate a time series of the most likely estimates of total annual run abundance. To simplify the description of the estimation process, the methodology is divided into 3 components based on the type of data used in the model: (1) escapement, (2) commercial harvest and effort, and (3) direct estimates of total run size for model scaling.

ESCAPEMENT COUNTS

Assuming the proportion of the total annual escapement returning to each tributary is constant, the expected escapement ($\hat{e}$) in year (y) to tributary (j) observed by method (i) (weir, aerial) is:

$$\hat{e}_{ijy} = E_y / k_{ij} \ , \tag{2}$$

where k_{ij} is a scaling parameter estimated by the model. The form of the negative binomial density presented in Hilborn and Mangel (1997) and Millar (2011) was used to model uncertainty in the count data. An additional parameter, typically called the overdispersion parameter ($\hat{m}_{ij}$), was estimated to account for additional variability. The likelihood of the combined observed escapements given the estimated parameters is:

$$L\left(e\middle|\hat{e},\hat{m},\hat{k}\right)=\prod_{y}\prod_{i}\prod_{j}\frac{\Gamma\left(\hat{m}_{ij}+e_{ijy}\right)}{\Gamma\left(\hat{m}_{ij}\right)e_{ijy}!}\left(\frac{\hat{e}_{ijy}}{\hat{m}_{ij}+\hat{e}_{iy}}\right)^{e_{ijy}}\left(\frac{\hat{m}_{ij}}{\hat{m}_{ij}+\hat{e}_{ijy}}\right)^{\hat{m}_{ij}}. \quad (3)$$

The root mean square error (RMSE) was calculated as the standard deviation of the differences between observed and predicted values for a given escapement estimate and were used as a measure of how well model predictions of escapement matched observations.

COMMERCIAL CATCH AND EFFORT

Assuming that commercial catch and run timing are known and accurate, commercial catch effort (f_{wky}) in week (w) with net configuration (k) is:

$$\hat{f}_{wky}=-\ln(1-c_{wky}/(p_{wy}N_y))/q_k. \quad (4)$$

Where:

c_{wky}: commercial catch at week (w) of net configuration (k),

p_{wy}: proportion of Chinook salmon available at week (w) based on Bethel test fishery, and

q_k: catchability coefficient of net configurations (k) (i.e., unrestricted, restricted).

Assuming the measurement error of weekly commercial catch efforts follows a lognormal distribution, the likelihood of the observed fishing effort given the estimated parameters is:

$$L\left(f\,\middle|\,\hat{f},\hat{q}\right)=\prod_{y}\prod_{w}\prod_{k}\frac{1}{\sigma_{\varepsilon}\sqrt{2\pi}}\exp\left(-\frac{\left(\ln f_{wky}-\ln\hat{f}_{wky}\right)^2}{2\sigma_{\varepsilon}^2}\right). \quad (5)$$

The concentrated likelihood function was used to eliminate the need for estimation of variance for commercial efforts.

MODEL SCALING

Direct estimates of total run size ($\hat{N}_y$)from the years 2003 to 2007 were derived from a combination of mark–recapture data, escapement estimates, extrapolation of escapement values to unmonitored areas, and harvests (Schaberg et al. 2012). Those estimates of total run and associated uncertainties were used to scale the run reconstruction model. The variance of the direct estimates (Schaberg et al. 2012) was used to represent measurement error associated with the model scalers. Assuming that measurement error follows a normal distribution, the likelihood of the observed total run given the estimated parameters is:

$$L\left(N\middle|\hat{N}\right)=\prod_{y}\exp\left(-\frac{\left(N_y-\hat{N}_y\right)^2}{2\sigma_{N_y}^2}\right). \quad (6)$$

LIKELIHOOD MODEL

The escapement, commercial harvest, and model scaling components were combined into a single likelihood model that simultaneously estimated the total run to the Kuskokwim drainage for each year:

$$L(\theta|data) = L\left(e\left|\hat{e}, \hat{m}, \hat{k}\right.\right) L\left(f\left|\hat{f}, \hat{q}\right.\right) L\left(N\left|\hat{N}\right.\right). \quad (7)$$

Parameter estimation was performed by minimizing the negative log-likelihood of the model using R optim (R Core Team 2014) with method "L-BFGS-B" (Appendix A).

RESULTS AND DISCUSSION

MODEL INPUTS

High water levels throughout much of the 2016 summer/fall season caused public concern that reliable escapement observations would be lacking to inform the run reconstruction model. This was not the case. Nearly all escapement projects operated effectively throughout all or most of the Chinook salmon run. The exception was the Kwethluk River weir, which was impacted by high water throughout much of the season. U.S. Fish and Wildlife Service successfully estimated the number of Chinook salmon that passed during times when the weir was compromised (Ken Harper, Fisheries Biologist, USFWS, Kenai; personal communication), and that total escapement estimate was used to inform the run reconstruction model. However, the uncertainty in the Chinook salmon escapement to the Kwethluk River was high (95% CI: 4,935–12,469 fish).

A considerable amount of information was available to inform the model and estimate total run and escapement in 2016. The 2016 model estimates were informed by direct observations of the 2016 escapement at 15 locations (5 weirs and 10 aerial surveys) combined with historical observations of escapement, harvest, and 5 years of mark–recapture data back to 1976 (Appendix B). No commercial harvest of Kuskokwim River Chinook salmon occurred during the 2016 season.

The escapement and harvest data indicate that the 2016 run of Chinook salmon to the Kuskokwim River was generally improved compared to the most recent years of low run size. A total of 9 (60%) projects reported higher escapements in 2016 compared to the recent 5-year average, 6 (40%) projects exceeded the recent 10-year average, and 3 (20%) projects exceeded the long-term average (Table 1). There are 10 tributaries with established escapement goals (Conitz et al. 2015), of which 9 were assessed in 2016. Of those, 4 were below the lower bound of the goal, 4 were within the goal range, and 1 exceeded the upper bound of the goal. Escapements to upriver tributaries in 2016 were some of the highest on record. Except Holitna River, escapements to middle river tributaries were generally poor in 2016 (i.e., Aniak, Holokuk, Oskawalik, George, Cheeneetnuk, and Gagaryah). The preliminary subsistence harvest of 30,676 Chinook salmon in 2016 was 90% larger compared to 2015 (Aaron Tiernan, Commercial Fisheries Biologist, ADF&G, Anchorage; personal communication), but still well below the amounts reasonably necessary for subsistence uses (ANS: 67,200–109,800).

MODEL RESULTS

The 2016 Kuskokwim River Chinook salmon drainagewide run was estimated to be 176,916 (95% CI: 134,407–232,871) fish (Table 2 and Figure 3). Coefficient of variation (CV) was estimated to be 16%, which is at the upper range of published historical estimates for years 1976–2015 (average: 11%, range: 7%–16%; Bue et al. 2012; Hamazaki and Liller 2015; Liller and Hamazaki 2016). The root mean square error (RMSE) was generally smaller for weirs compared to aerial surveys, indicating the model fit the weir data better than aerial survey data (Figure 4). Larger overdispersion parameters for weir data (Table 3) compared to aerial survey data show that the model put higher weight on weir observations. Estimates of total annual abundance for years 1976–2015, generated by the 2016 model run, were on average 9% (24,473 fish) larger than previously reported estimates, but well within the previously published 95% confidence intervals (Table 2 and Figure 5).

Chinook salmon run sizes in recent years are well below the 1976–2015 average, but have been improving. Seven of the 9 smallest run sizes have been observed since 2010. The 2016 run was the largest observed since 2009 and was nearly double the 2013 run, which was the smallest run on record. Although run sizes have improved annually since 2013, the 2016 run was 31% smaller than the long-term average (1976–2015) of 257,168 Chinook salmon. The 2016 run was within the range of run sizes capable of supporting some fisheries, and was larger than the 1986 and 2000 runs, both of which supported unrestricted subsistence harvest opportunities and were followed by periods of healthy returns (Table 2 and Figure 3).

The 2016 Kuskokwim River Chinook salmon drainagewide escapement was estimated to be 145,718 (95% CI: 103,209–201,673) fish. Based on the 2016 model run, total escapement in 2016 was 13% less than the recent long-term average (1976–2015) of 166,969 Chinook salmon. Total escapement in 2016 was greater than 19 of 40 (48%) past years. Although the uncertainty of the drainagewide escapement is relatively high, the 95% confidence range (103,209–201,673 fish) provides considerable evidence that the drainagewide escapement goal of 65,000–120,000 was exceeded (Table 2 and Figure 3).

UNCERTAINTY OF 2016 MODEL ESTIMATES

The uncertainty observed in 2016 is similar to observations in 2014 and 2015, but notably higher compared to all other years since 1987 (Figure 6a). In general, the uncertainty about any particular years' model estimate is related to: (1) the number of index projects that operated in that year and (2) the similarity in the information about the total run provided by each project. The number of index projects operated in 2016 was in the top 20% (i.e., greater than 32 prior years), which would suggest a large amount of information to inform the model and a relatively low level of uncertainty. However, in 2016 some index projects indicated the total escapement was very small whereas others indicated the escapement was very large. The model is specifically designed to accommodate "conflicting" data from a range of index projects; however, greater differences among projects results in greater uncertainty in the actual size of the total run and escapement. In order to illustrate this, the entire drainagewide escapement was estimated with data from only 1 project at a time, and all estimates were compared (Figure 7). In 2016, estimates of drainagewide Chinook salmon escapements derived from each weir project ranged from 73,700 to 213,300 fish whereas estimates derived from aerial survey projects ranged from 30,600 to 423,400 fish (Figure 7).

Relatively high model uncertainty in 2014, 2015, and 2016 may be related to changes in fish distribution. Each tributary escapement project is related to the drainage escapement by a scaling factor that is estimated by the model and is assumed to be constant over time (Equation 2). The assumption that spawning distribution is constant over time may no longer be valid because harvest restrictions imposed on the fishery have changed fishing patterns. Specifically, subsistence harvest during the early portion of the annual run has been heavily restricted since 2014, greatly reducing exploitation on early migrating fish. There is compelling evidence that high proportions of these early migrating fish spawn in more distant portions of the drainage (ADF&G *unpublished data*). The reduced exploitation of these sub-stocks may explain the larger than expected escapements to Tatlawiksuk River, Salmon (Pitka) Fork, and Bear Creek since 2014. Changes in spawning distribution relative to past years could result in misleading model results. For example, the very large Chinook salmon counts to upriver tributaries would suggest that the total escapement was near record high (Figure 7). Clearly this was not the case because the bulk of the information from other index projects indicates the annual escapements were below average.

Sensitivity of the model results to the input data was explored (Figure 8). In particular, the model was rerun twice, first we used only weir data and then we used only aerial survey data. In both cases, the point estimate fell within the 95% confidence interval of the ADF&G base model and the confidence intervals overlapped broadly. This suggests that weirs and aerial survey data provided a similar overall estimate of total run in 2016. In addition, the model was rerun using the smallest and largest estimate of Kwethluk River weir escapement (95% CI: 4,935–12,469 fish) to evaluate the influence of the uncertainty associated with that particular project. Both model runs produced similar estimate compared to the ADF&G base model, suggesting that the 2016 total run estimate was not sensitive the uncertainty in the Kwethluk escapement. Finally, the model was rerun after removing data from upriver escapement monitoring locations (i.e., Tatlawiksuk River, Salmon (Pitka) Fork, and Bear Creek) in order to evaluate the influence of the large escapements observed in these systems, which is thought to be a result of early season fishery closures. Removal of these 3 projects' data resulted in a 24% reduction in the total run estimate and the point estimate fell outside the 95% confidence interval of the base model. This result would suggest that the relationship between total escapement and observed escapement to upriver tributaries has changed and a formal evaluation of model scaling is warranted.

MODEL REVIEW CONSIDERATIONS

Model scaling is an important factor that influences the ability to accurately estimate total run and escapement. The model is currently scaled using 5 years of total run estimates from 2003 to 2007 (Figure 3). The run abundance in each of those 5 years was above average and included record high abundances in 2004 and 2005 (Schaberg et al. 2012). The record low run sizes beginning in 2010 are outside the parameters on which the model has been based.

The ADF&G Division of Commercial Fisheries has completed a 3 year (2014–2016) effort to evaluate model scaling during years of low run abundance (ADF&G *unpublished data*). This effort included large-scale mark–recapture studies to estimate Chinook salmon abundance as well as visual and telemetry surveys to validate methods used for estimating escapement to unmonitored tributaries in the lower Kuskokwim River. Preliminary estimates of total run size based on mark–recapture methods are 78,600 fish (95% CI: 67,300–98,100) in 2014, 122,400 fish (95% CI: 112,000–132,600) in 2015, and 128,800 fish (95% CI: 110,100–155,300) in 2016. The most recent mark–recapture estimates are not directly comparable to the existing model scalars because the location of the tag site changed as well as methods for estimating escapement to unmonitored tributaries downriver of the tag site.

The 2014–2016 mark–recapture information does provide an opportunity to informally gauge model performance. A direct comparison illustrates that the estimates from the mark–recapture study are, on average, 31% smaller (approximately 48,000 fish) compared to the estimate of total run based on the published model (Figure 9). Inclusion of the preliminary 2014–2016 mark–recapture estimates into the existing model is a logical first step to explore the potential influence on the historical time series. As expected, smaller total run estimates are produced for all years

(1976–2016); however, both time series are well within the 95% confidence interval around the run estimates produced by Bue et al. 2012 which were used to establish the escapement goal (Figure 10). Discussion of the 2014–2016 mark–recapture information at this time is intended to provide insight into run reconstruction model performance and highlight the need for ongoing model reviews and collaborative efforts to update the model.

The 2014–2016 mark–recapture information is not ready for formal inclusion into the run reconstruction model. First, the Kuskokwim River Interagency Model Development Team must determine the best way to standardize all years of mark–recapture information (2003–2007, 2014–2016). More importantly, incorporation of the new mark–recapture information is only one part of the model review and update process. The KRIMDT will consider potential revisions to the model structure to better accommodate changes to the management of the fishery that occurred after the original model was published. The team must also consider options for weighting different data types and the best way to handle changes in the assessment program, both historically and moving forward. Each of these important considerations will benefit from pending independent advice from the AYKSSI model review process. Perhaps most important, evaluation of the existing drainagewide escapement goal is directly tied to the published run reconstruction model. Any efforts to rescale the model must be followed by a formal review of the escapement goal which will not occur until the ongoing model review and update efforts are completed.

Allowing the model review process to play out does not preclude consideration of the mark–recapture results to help draw broad conclusions about abundance and escapement trends. Regardless of which method is used, there is considerable evidence that annual run size has increased each year since 2013 (Figure 11a). Similarly, general conclusions about escapement goal performance are consistent regardless of which method is used (Figure 11b). Although the published run reconstruction model indicates the escapement goal was exceeded annually since 2014, the lower bound of the 95% confidence interval is within the escapement goal range each year. There is considerable evidence that the escapement goal was at least met in each year since 2014.

2016 RUN RECONSTRUCTION MODEL CONCLUSIONS

- The total run of Kuskokwim River Chinook salmon was estimated to be 176,916 (95% CI: 134,407–232,871) fish (Table 2).
- Total run abundance was below average, but within a range of run sizes that could likely support subsistence harvest at levels near the lower bound of amounts necessary for subsistence (67,200–109,800) as defined by the Alaska Board of Fisheries 5 AAC 01.2086.
- The total escapement of Kuskokwim River Chinook salmon was estimated to be 145,718 (95% CI: 103,209–201,673) fish (Table 2).
- Total escapement was near average due to harvest restrictions throughout much of Chinook salmon run and the drainagewide sustainable escapement goal of 65,000–120,000 was likely exceeded (Table 2).
- Results from mark–recapture studies indicates that the true size of the 2016 run and escapement may be better represented by the lower bound of the 95% confidence range surrounding the run reconstruction model estimate (Figure 9).

2017 CHINOOK SALMON RUN FORECAST

The 2017 Kuskokwim River Chinook salmon forecast is for a range of 132,000–222,000 fish. The forecast range is equal to ±25% of the 2016 total run estimated using the published run reconstruction model as presented in this report. Uncertainty in the forecast (i.e., ±25%) is based on the recent 7-year (2010–2016) average percent deviation in subsequent year run sizes. The forecast is not based on probability and alone provides no insight into the most likely run size within the forecasted range. Therefore, additional information such as recent year abundance trends, stock productivity, age-class relationships, and other abundance information (e.g., mark–recapture) should be considered when using this forecast to plan preseason management of the 2017 Chinook salmon run.

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TABLES AND FIGURES

Table 1.–Historical and recent year observations of Kuskokwim River Chinook salmon abundance used to inform run reconstruction models.

Method	Location	Number of years of data (1976–2016)	Historical average (1976–2015)	10-yr average (2006–2015)	5-yr average (2011–2015)	2015	2016
Weir	Kwethluk	15	8,879	6,612	4,068	8,162	7,619
	Tuluksak	20	1,010	474	412	709	909
	George	18	3,529	2,641	2,063	2,282	1,663
	Kogrukluk	31	10,242	8,207	5,091	8,081	7,056
	Tatlawiksuk	17	1,577	1,304	1,322	2,104	2,494
	Takotna [a]	16	417	290	154	–	–
Aerial Survey	Kwethluk [b]	11	2,183	826	1,165	–	–
	Kisaralik	24	1,166	1,157	630	709	622
	Tuluksak [b]	12	392	128	83	–	–
	Salmon (Aniak)	30	814	519	318	810	–
	Kipchuk	24	1,023	942	541	917	898
	Aniak	21	2,797	3,360	1,978	–	718
	Holokuk	15	365	271	64	77	100
	Oskawalik	20	304	185	79	–	47
	Holitna	19	1,664	1,020	597	662	1,157
	Cheeneetnuk	22	725	369	239	–	217
	Gagaryah	21	463	283	145	19	135
	Pitka [c]	11	221	148	–	–	–
	Bear	18	255	321	509	1,318	580
	Salmon (Pitka)	28	999	939	1,157	2,016	1,578
Harvest	Subsistence	41	68,986	58,801	31,877	16,124	30,676
	Commercial	41	20,120	2,281	318	8	0

Note: Not all projects operated in all years. Average represents only years when the project operated successfully.

[a] Weir operated from 1995 until 2013.

[b] Aerial surveys not flown since 2013 because system is monitored by a weir.

[c] Aerial surveys not flown since 2011.

Table 2.–Annual drainagewide run and escapement of Kuskokwim River Chinook salmon from the 2016 run reconstruction model.

		2016 Model Run				2016 Model Run		
Year	Published Total Run Estimate	2016 Total Run Estimate	Lower 95% CI	Upper 95% CI	Published Total Esc. Estimate	2016 Total Esc. Estimate	Lower 95% CI	Upper 95% CI
1976	233,967	242,003	184,422	317,562	143,420	151,456	93,875	227,015
1977	295,559	335,824	261,113	431,912	201,852	242,117	167,406	338,205
1978	264,325	298,973	235,156	380,109	180,853	215,501	151,684	296,637
1979	253,970	310,656	231,936	416,094	157,668	214,354	135,634	319,792
1980	300,573	320,274	233,769	438,789	203,605	223,306	136,801	341,821
1981	389,791	425,967	323,412	561,042	279,392	315,568	213,013	450,643
1982	187,354	217,095	178,030	264,731	80,353	110,094	71,029	157,730
1983	166,333	193,405	150,823	248,009	84,188	111,260	68,678	165,864
1984	188,238	217,437	164,789	286,906	99,062	128,261	75,613	197,730
1985	176,292	189,676	142,018	253,328	94,365	107,749	60,091	171,401
1986	129,168	134,290	99,491	181,260	58,556	63,678	28,879	110,648
1987	193,465	209,825	150,076	293,360	89,222	105,582	45,833	189,117
1988	207,818	256,002	229,508	285,555	80,055	128,239	101,745	157,792
1989	241,857	283,042	227,645	351,919	115,704	156,889	101,492	225,766
1990	264,802	285,561	239,420	340,593	100,614	121,375	75,234	176,407
1991	218,705	231,179	191,270	279,415	105,589	118,031	78,122	166,267
1992	284,846	300,362	248,316	363,317	153,573	169,089	117,043	232,044
1993	269,305	309,606	243,932	392,960	169,816	210,095	144,421	293,449
1994	365,246	436,285	322,609	590,016	242,616	313,655	199,979	467,386
1995	360,513	412,661	328,878	517,788	225,595	277,743	193,960	382,870
1996	302,603	365,732	274,910	486,559	197,092	260,221	169,399	381,048
1997	303,189	363,258	276,875	476,591	211,247	271,877	185,494	385,210
1998	213,873	208,072	155,434	278,536	113,627	107,856	55,218	178,320
1999	189,939	183,963	144,690	233,896	112,082	106,133	66,860	156,066
2000	136,618	146,860	123,302	174,919	65,180	78,627	55,069	106,686
2001	223,707	255,036	203,769	319,200	145,232	176,561	125,294	240,725
2002	246,296	252,388	209,194	304,499	164,635	170,727	127,533	222,838
2003	248,789	275,814	233,581	325,684	180,687	207,712	165,479	257,582
2004	388,136	412,906	346,437	492,129	287,178	312,265	245,796	391,488
2005	366,601	391,160	333,594	458,659	275,598	300,157	242,591	367,656
2006	307,662	336,272	280,083	403,733	214,004	242,614	186,425	310,075
2007	273,060	281,473	243,304	325,629	174,943	183,356	145,187	227,512
2008	237,074	244,120	209,441	284,543	128,978	136,024	101,345	176,447
2009	204,747	213,511	179,459	254,025	118,478	127,242	93,190	167,756
2010	118,507	124,789	108,945	142,938	49,073	55,355	39,511	73,504
2011	133,059	133,236	114,758	154,689	72,097	69,205	50,727	90,658
2012	99,807	100,488	78,524	128,595	76,074	76,996	55,032	105,103
2013	94,166	91,061	79,534	104,258	47,315	43,573	32,046	56,770
2014	135,749	131,624	99,336	174,406	123,987	119,858	87,570	162,640
2015	172,055	164,821	123,826	219,387	155,464	148,217	107,222	202,783
2016		176,916	134,407	232,871		145,718	103,209	201,673
Average (19762015)	234,694	257,168	(Diff. = 22,473 or 9%)		144,477	166,965	(Diff. = 22,489 or 15%)	

Note: The run reconstruction model revises estimates for all years when the model is updated with new information. The full time series associated with the 2016 run and escapement estimate is shown here for transparency. The estimates shown here for years 1976–2015 do not supersede previously published estimates.

Table 3.–Parameter estimates derived from the 2016 run reconstruction model.

	Parameter	95% Bound		Overdispersion
	Estimate	Lower	Upper	Parameter (*m*)
Weir Projects (*k*)				
Kwethluk Weir	19.16	14.80	24.80	7.02
Tuluksak Weir	178.77	138.91	230.06	6.32
George Weir	44.31	34.87	56.30	9.98
Kogrukluk Weir	16.48	13.35	20.33	9.82
Tatlawiksuk Weir	85.52	68.42	106.88	16.44
Takotna Weir	383.86	297.66	495.01	8.41
			Average	9.66
Aerial Survey (*k*)				
Kwethluk River	87.82	59.13	130.42	2.72
Kisaralik River	160.23	112.27	228.66	1.64
Tuluksak River	485.93	338.34	697.89	3.41
Salmon (Aniak River)	229.16	174.92	300.23	3.01
Kipchuk River	171.69	132.45	222.56	4.32
Aniak River	65.32	50.38	84.69	5.13
Holokuk River	485.58	312.11	755.45	1.56
Oskawalik River	652.00	452.30	939.87	1.94
Holitna River	106.69	79.75	142.73	4.50
Cheeneetnuk River	248.73	182.02	339.89	3.05
Gagaryah River	413.04	310.81	548.89	3.82
Pitka Fork	765.26	571.82	1024.13	6.61
Bear River	729.95	538.70	989.08	3.96
Salmon(Pitka Fork)	150.59	115.62	196.14	3.89
			Average	3.54
Catchability (*q*)				
Unrestricted	7.04E-05	5.65E-05	8.78E-05	
Restricted (1)	1.32E-05	1.00E-05	1.74E-05	
Restricted (2)	4.04E-05	3.30E-05	4.95E-05	

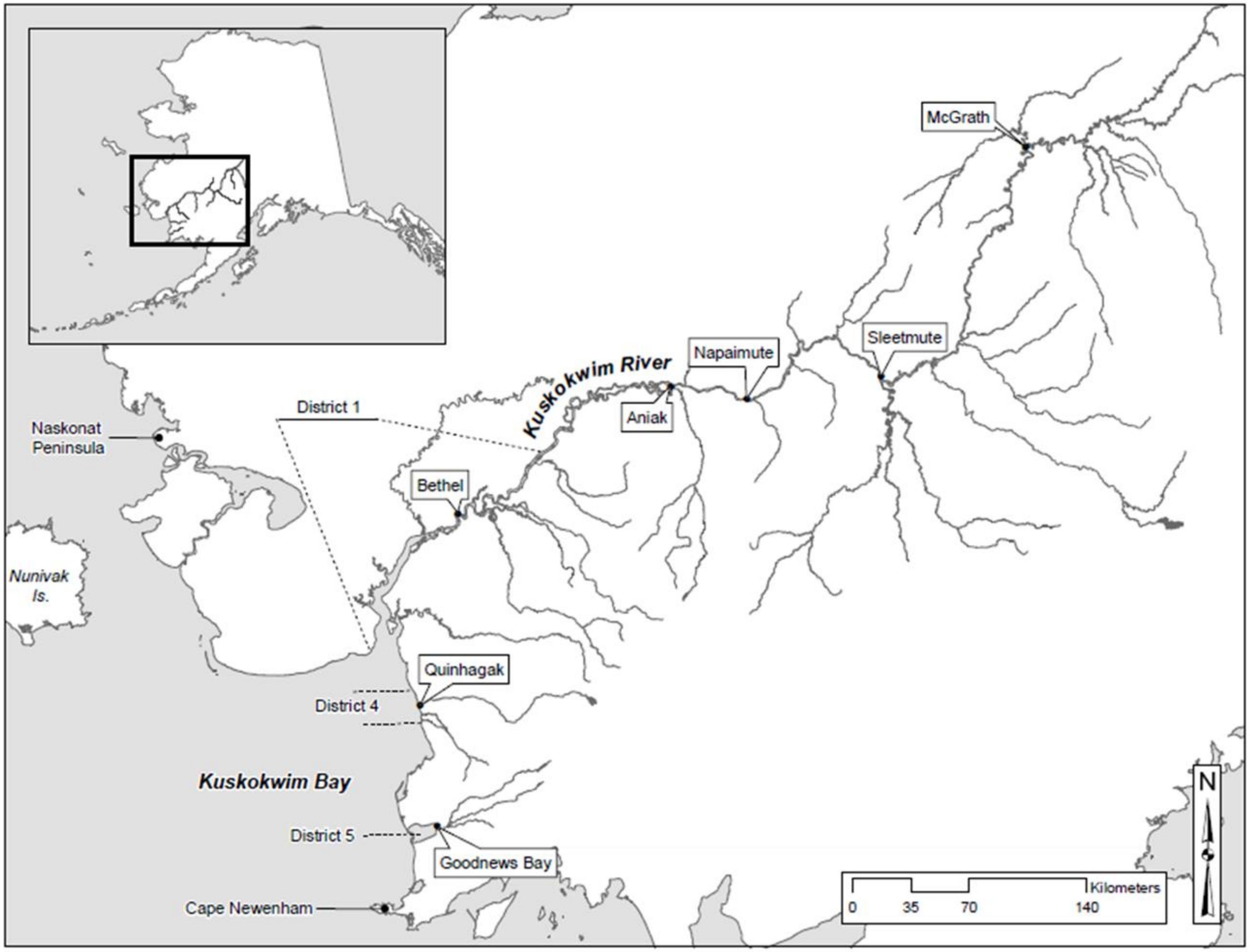

Figure 1.–Kuskokwim Management Area showing major communities and commercial fishing districts.

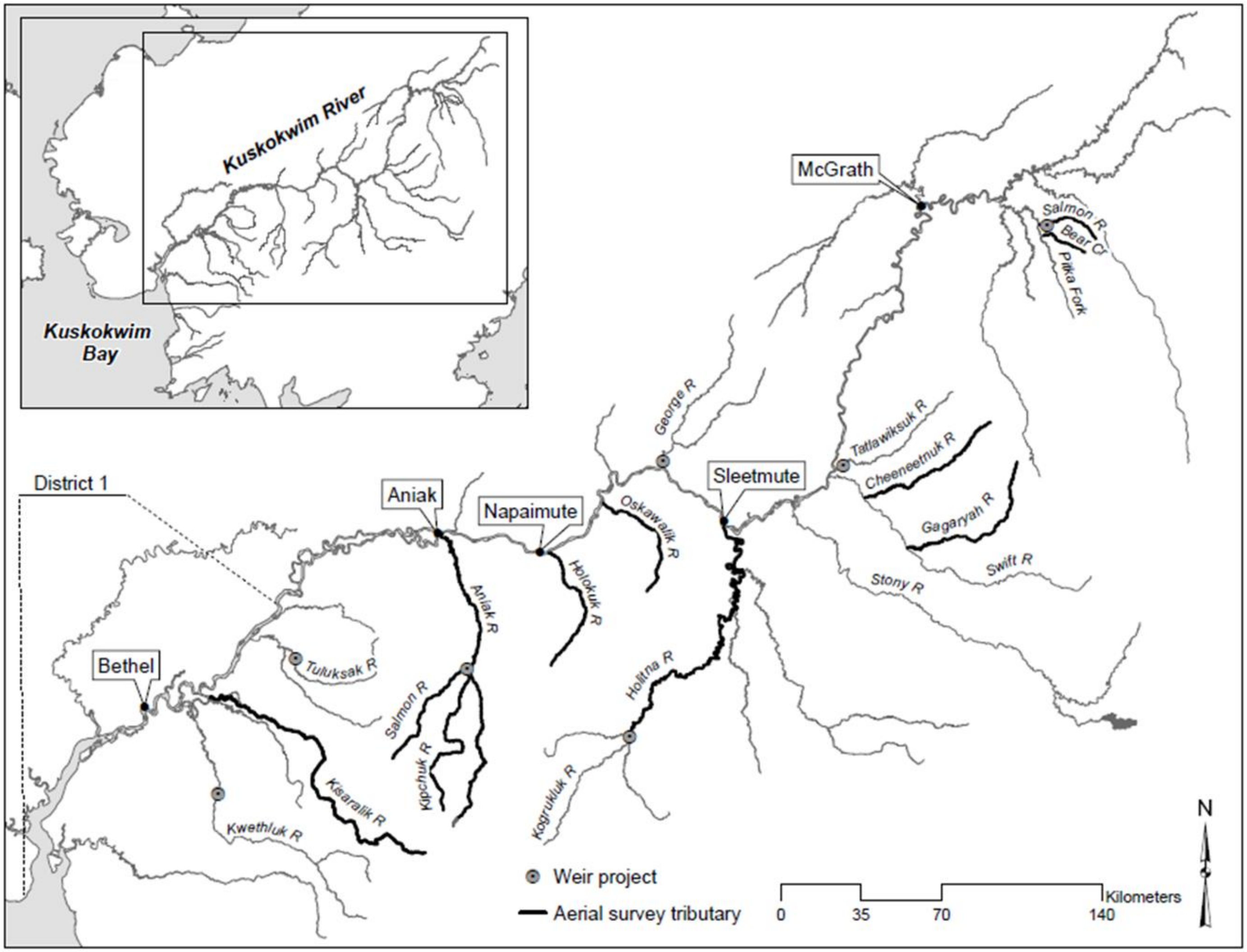

Figure 2.–Kuskokwim River tributaries where Chinook salmon escapement was monitored in 2016.

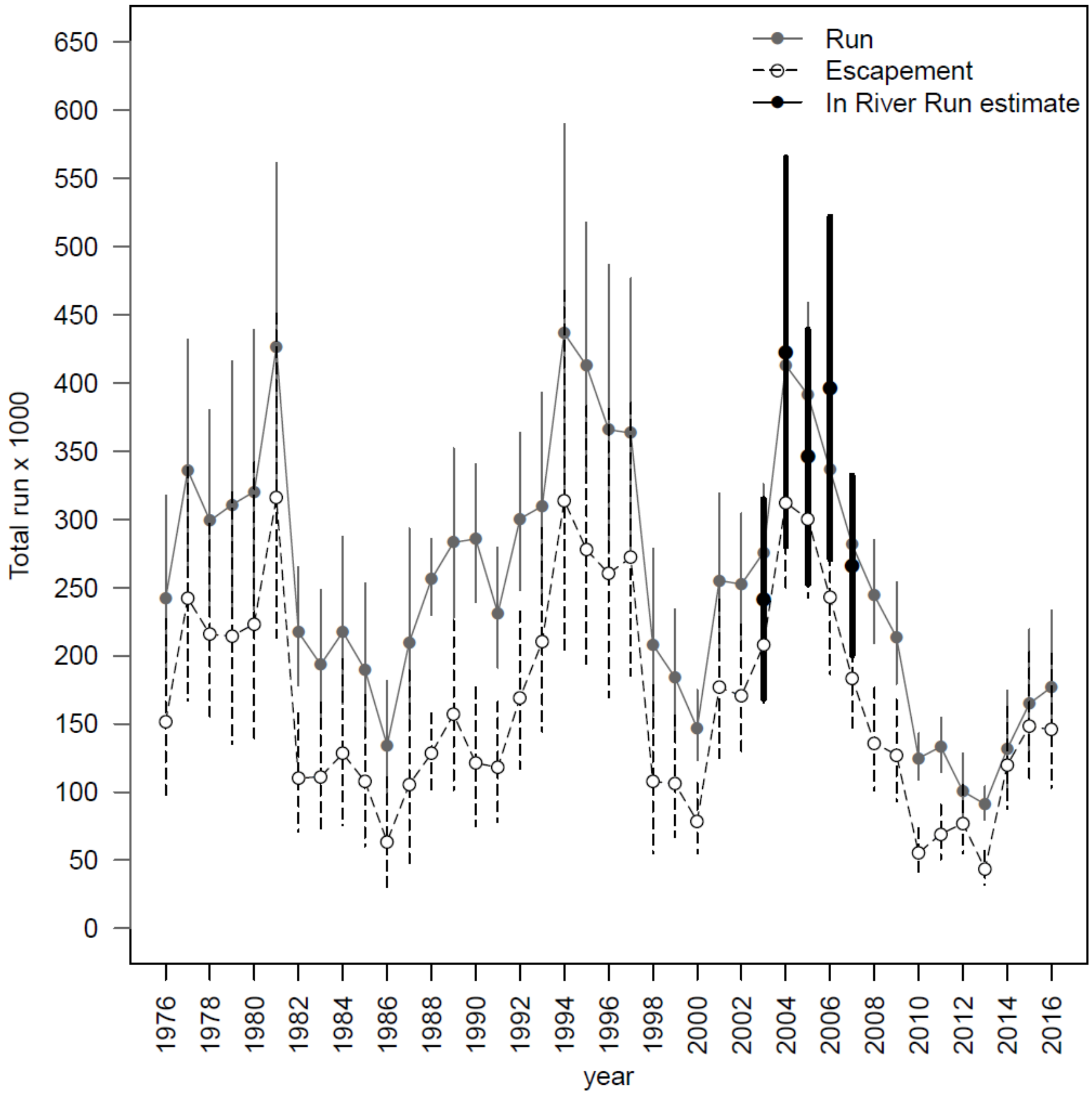

Figure 3.–Annual run (grey) and escapement (white) estimates with 95% confidence intervals estimated from the 2016 run reconstruction model. Black dots are the observed drainagewide run sizes and 95% confidence intervals for years 2003–2007 used to scale the model.

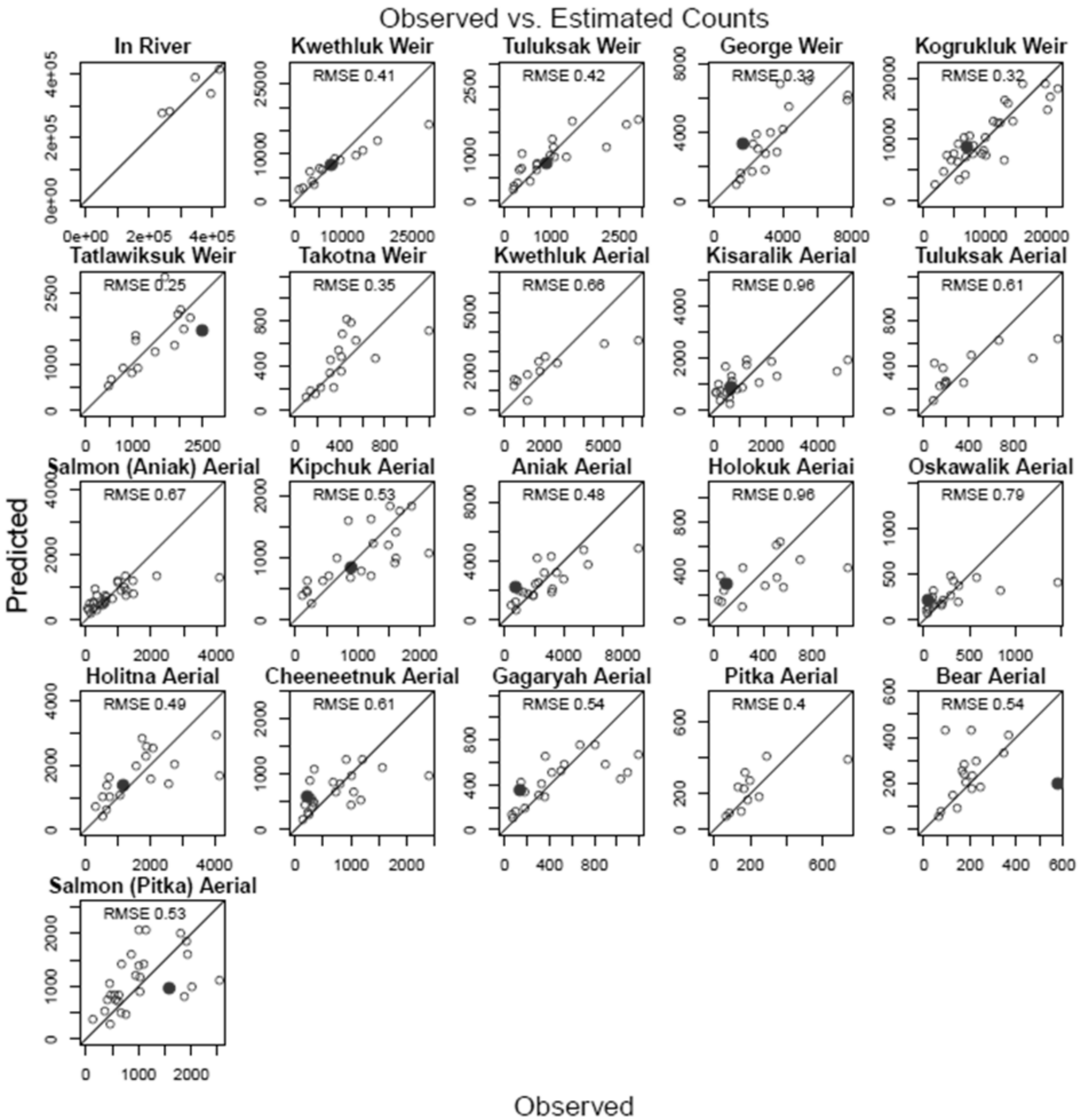

Figure 4.–Observed versus model estimated escapement counts. The diagonal line within each subplot represent the 1:1 line, which is the point at which observed and estimated escapements are equal. Hollow dots are the prior year observations and solid dots are the 2016 observations. Dots that fall below the 1:1 line indicate that the observed counts are higher than the model estimates, and the opposite is also true. The top left subplot titled "Inriver" is the 2003–2007 total run estimates used to scale the model.

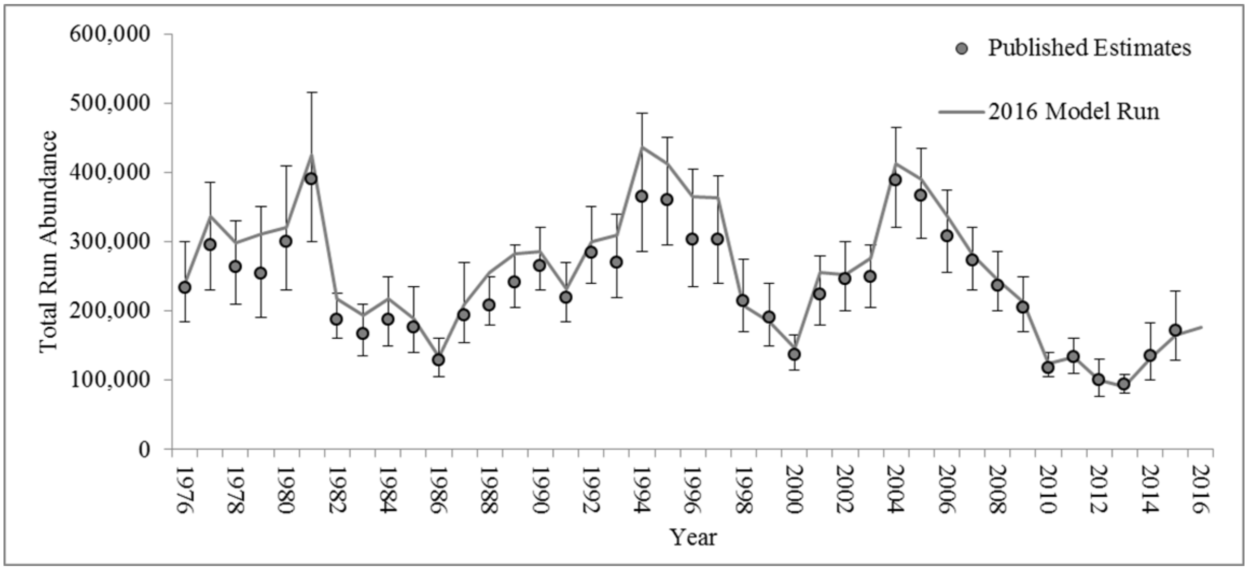

Figure 5.–Comparison of 2016 model run reconstruction estimates of total Kuskokwim River Chinook salmon run size and previously published results (95% confidence intervals) reported by Bue et al. 2012; Hamazaki and Liller 2015; and Liller and Hamazaki 2016.

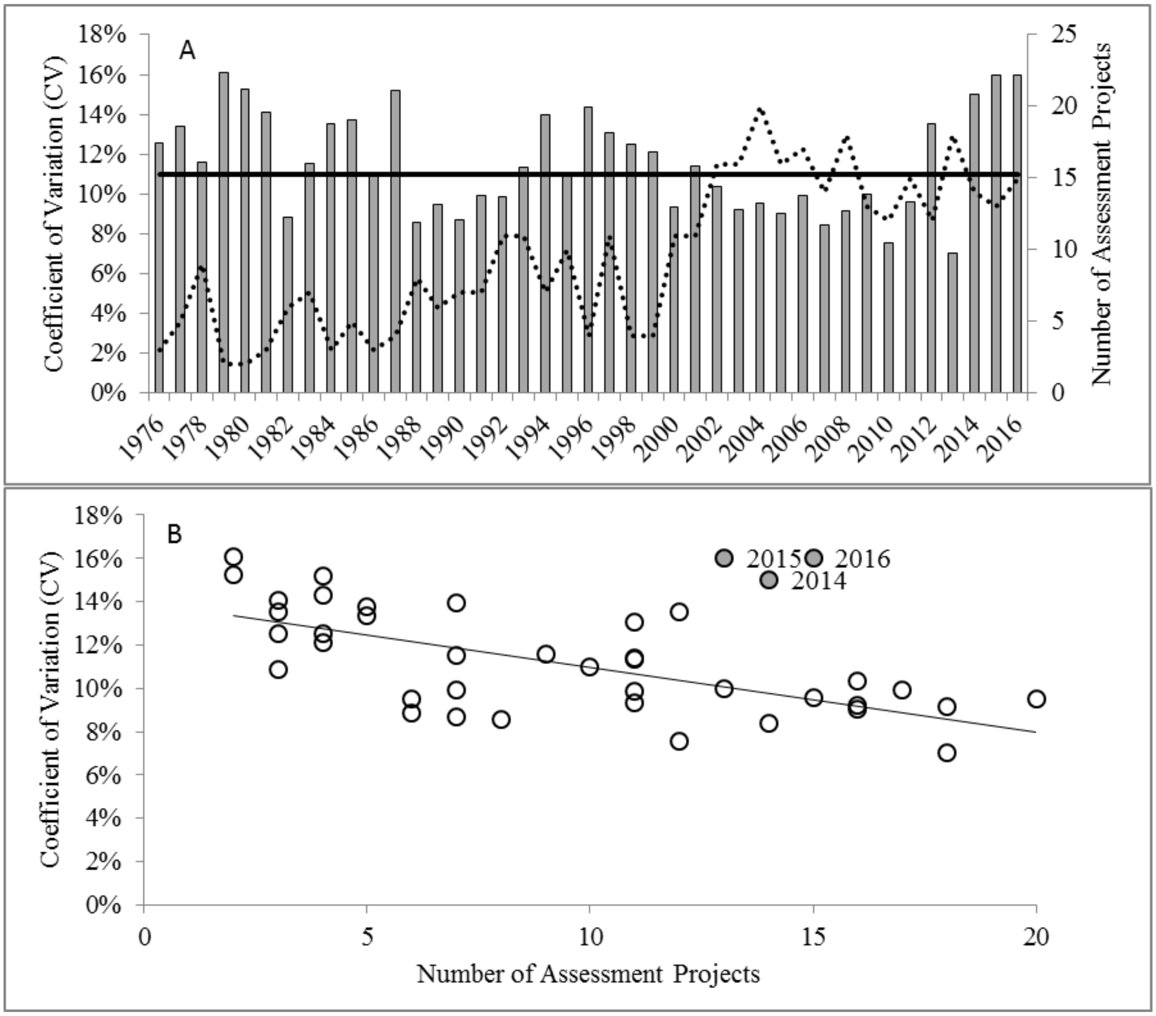

Figure 6.–Annual uncertainty (coefficient of variation) of the run reconstruction model estimate of total run size and relationship between uncertainty and the number of assessment projects used to inform the model in each year. The top graph (A) illustrates the annual coefficient of variation (grey bars). The solid black line is the average coefficient of variation (11%) across years 1976–2015. The number of projects operated annually is represented by the dotted black line. The bottom graph (B) illustrates the relationship between coefficient of variation and the number of assessment projects available to inform the annual model estimate. The most recent years 2014–2016 are highlighted.

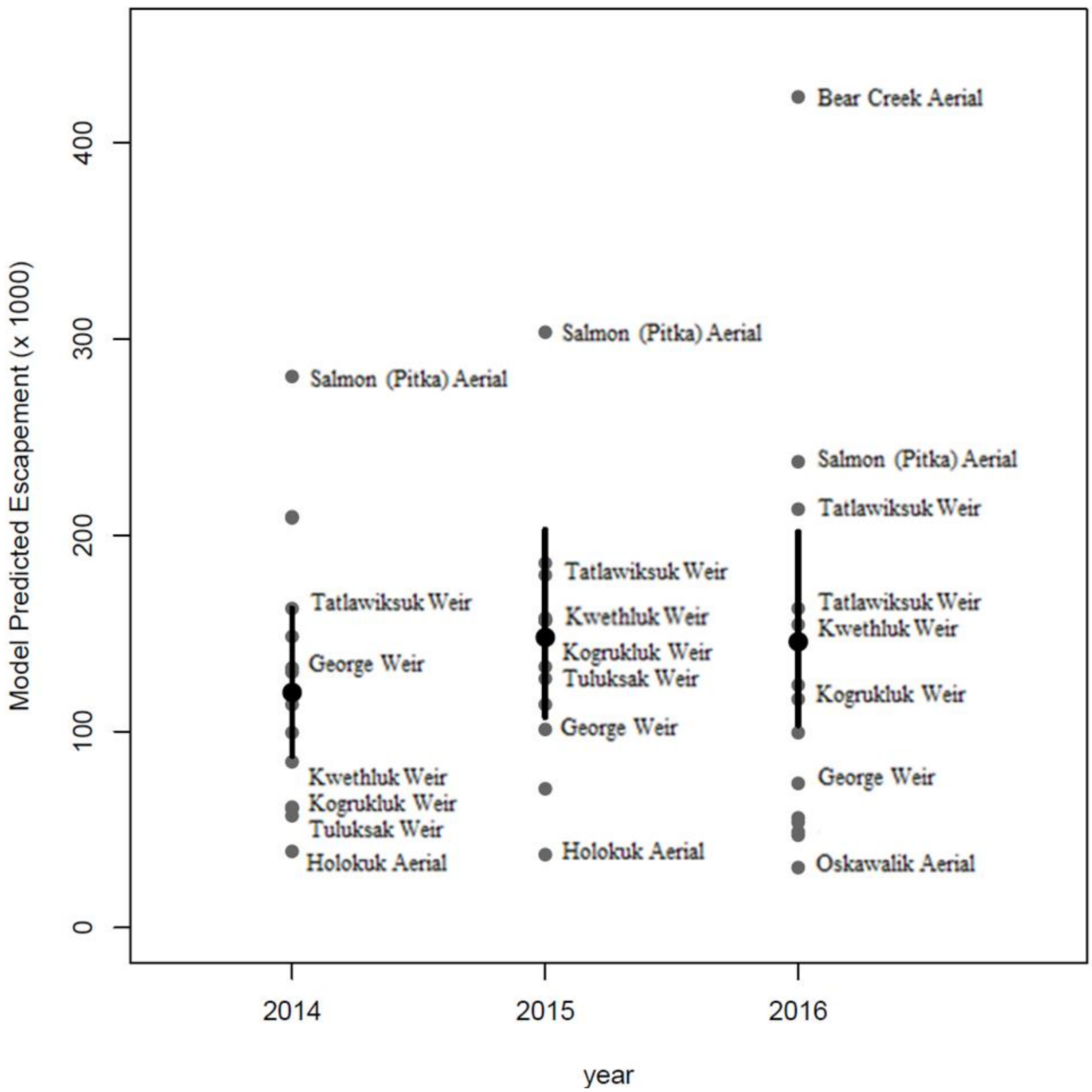

Figure 7.–Range of drainagewide escapement estimates produced by the model based on each individual escapement project. Grey dots are individual project estimates of total run based on the model estimated scaling factor. Black dot and line shows the model derived drainagewide escapement and 95% confidence interval after simultaneously combining the information from all escapement monitoring projects. The more similar the project estimates the tighter the confidence range around the drainagewide estimate. 2014 and 2015 are shown to provide context.

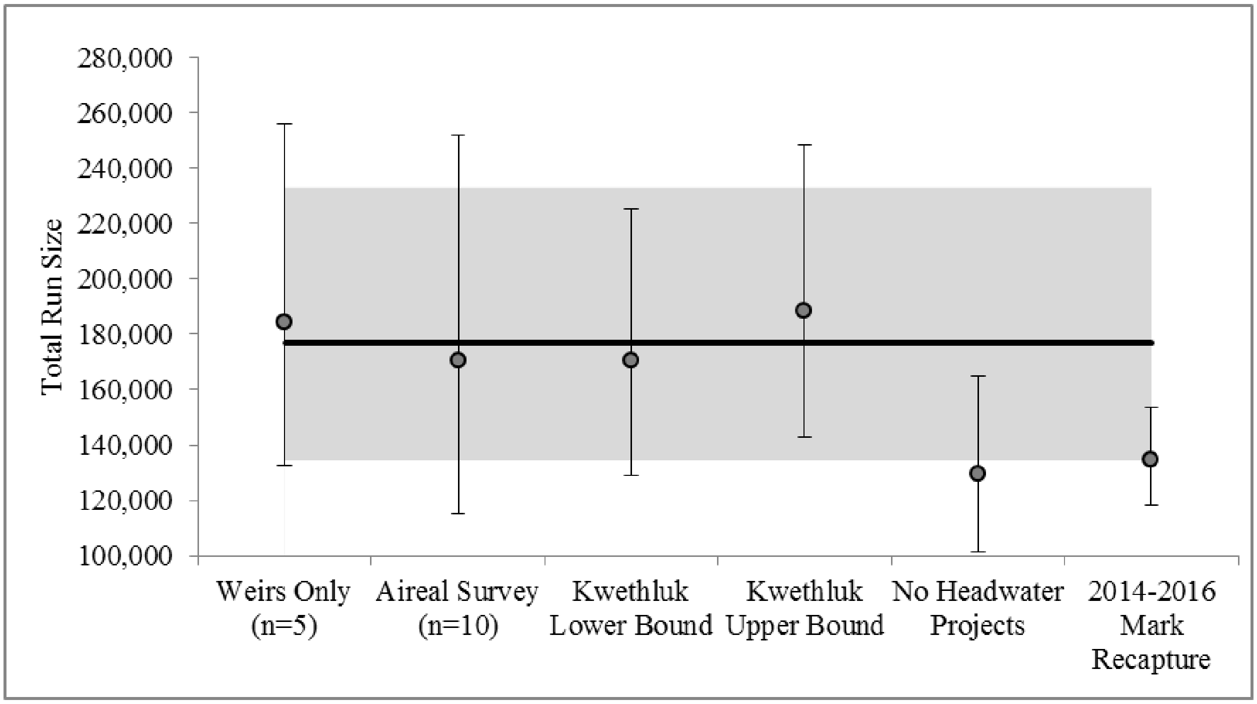

Figure 8.–Sensitivity of total Chinook salmon run size estimates using weir data only, aerial survey data only, the lower/upper bounds of the Kwethluk River weir estimate, exclusion of data from headwater projects, and inclusion of the 2014–2016 mark–recapture estimates as additional scalars. The solid black line is the point estimate of the ADF&G base model and the grey shaded area is the 95% confidence interval. Alternative estimates (grey dots) and 95% confidence intervals are shown for comparison. The amount of overlap with the grey shaded area indicates the degree of similarity between estimates.

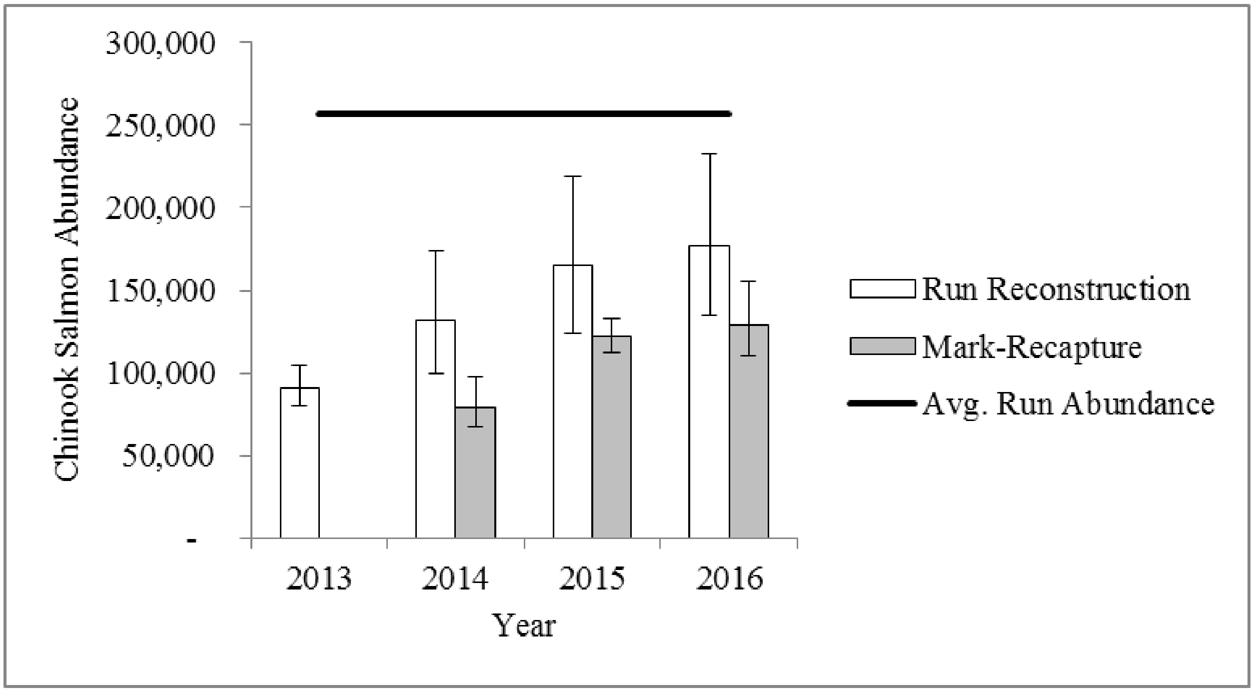

Figure 9.–Estimates of total run size of Kuskokwim Chinook salmon using the 2016 run reconstruction and preliminary mark–recapture methods, 2013–2016.

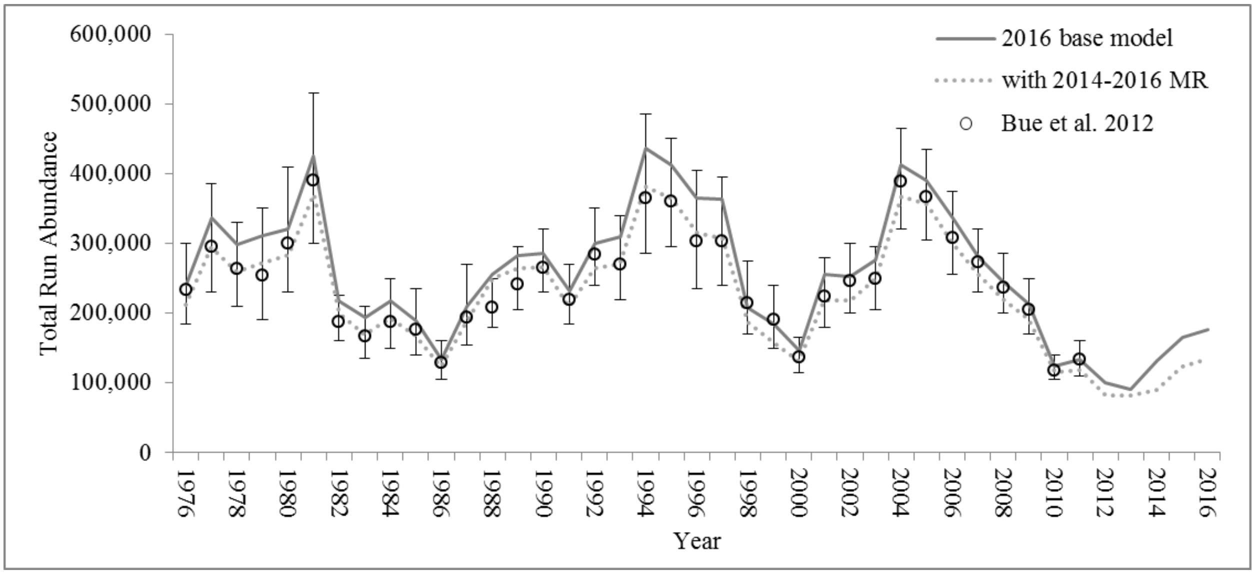

Figure 10.–Comparison of estimates of Kuskokwim River Chinook salmon total run size (95% confidence intervals) as reported by Bue et al. (2012) with the 2016 run reconstruction model results with and without the 2014–2016 mark–recapture scalars.

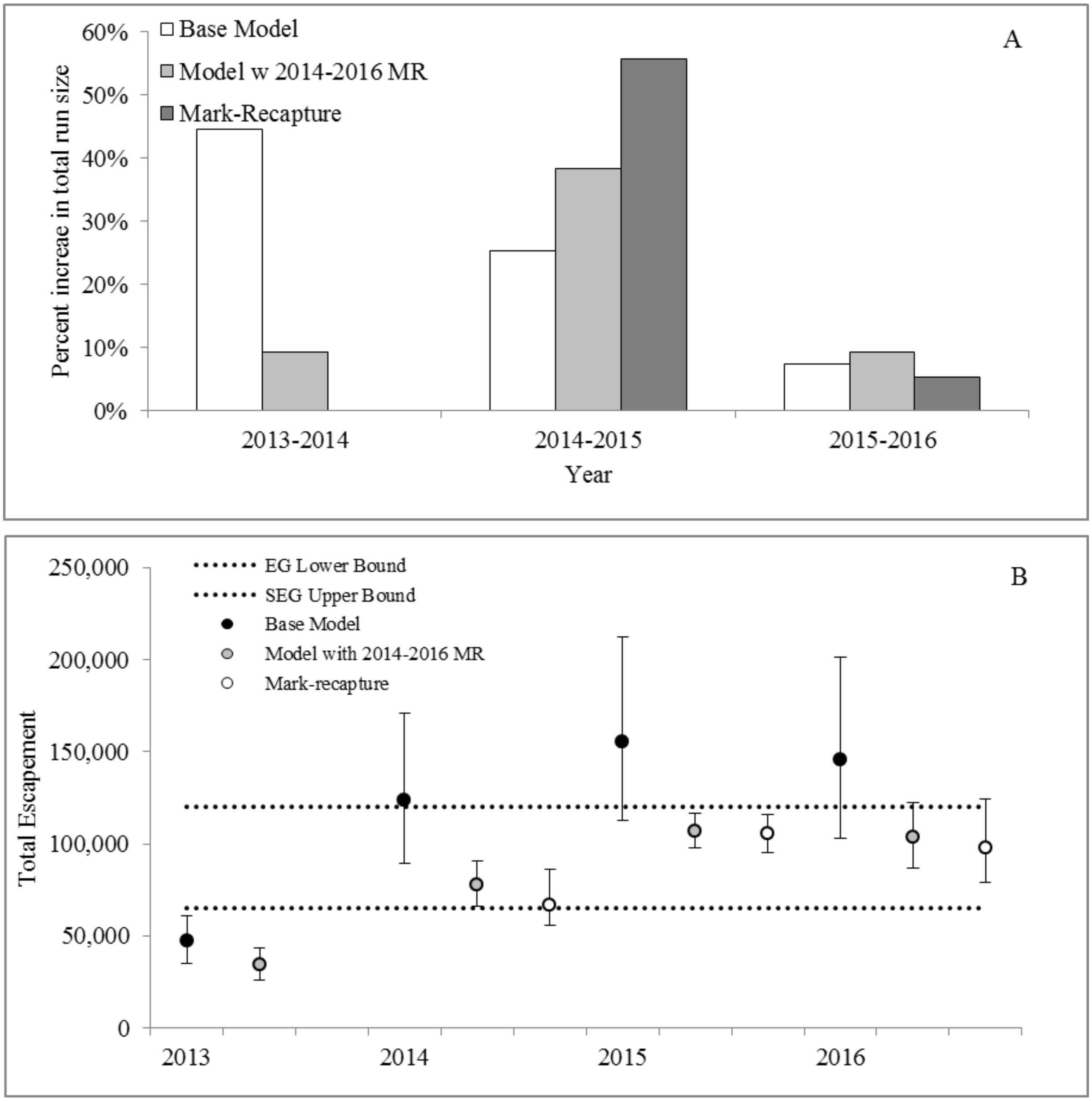

Figure 11.–Comparison of general conclusions about Kuskokwim River Chinook salmon total run abundance and escapement based on the published run reconstruction model, the model with inclusion of the 2014–2016 mark–recapture data, and the mark–recapture based abundance estimates. The top figure (A) illustrates the percent increase in total run size between successive years. The bottom figure (B) illustrates the escapement goal performance in 2013–2016. Escapement estimates derived using the model with 2014–2016 mark–recapture and mark–recapture only methods are provided for comparison to illustrate similarities in general conclusions.

APPENDIX A: 2016 R-CODE WITH ANNOTATIONS

```
###################################################################################
# 1.0 Initialize working Environment
###################################################################################
rm(list=ls(all=TRUE))
# Enter the name of data file
data_file <- 'Kusko_RR_Input_March_10_2016.csv'
kusko.data <- read.csv(data_file,header=T, na.string='')
###################################################################################
# 2.2 Test fishery: Estimate run proportion of 1976-1983
###################################################################################
# Extract testfish data
testf<-kusko.data[substr(names(kusko.data),1,3)=='rpw']
# combine week 8, 9 and 10 and drop
testf[,8] <- testf[,8]+testf[,9]+testf[,10]
testf <- testf[,-(9:10)]
# Replace NA to mean proporion for each week
for (i in 1:dim(testf)[2]) {
  testf[is.na(testf[i]),i] <- colMeans(testf,na.rm=T)[i]
}
###################################################################################
# 2.3 Rearrange fishing effort and harvest data catch 0 to NA
###################################################################################
# Extract weekly commercial effort data
ceff <-kusko.data[substr(names(kusko.data),1,3)=='cew']
# combine week 8, 9 and drop
ceff[,6] <- ceff[,6]+ceff[,7]
ceff <- ceff[,-7]
# replace 0 to NA
ceff[ceff == 0] <- NA
# Extract weekly commercial catch data
ccat <-kusko.data[substr(names(kusko.data),1,3)=='chw']
```

```
# combine week 8, 9 and drop
ccat[,6] <- ccat[,6]+ccat[,7]
ccat <- ccat[,-7]
# replace 0 to NA
ccat[ccat == 0] <- NA
# Extract weekly commercial est data
creg <-kusko.data[substr(names(kusko.data),1,3)=='cfw']
# combine week 8, 9 and drop
creg[,6] <- pmax(creg[,6],creg[,7])
creg <- creg[,-7]
#######################################################################################
# 2.4 Recalculate Inriver data
#######################################################################################
# Extract Inriver data
inr <-kusko.data[substr(names(kusko.data),1,3)=='In.']
# Calculate CV
inr$cv <- inr$In.river.sd/inr$In.river
#######################################################################################
# 2.5 Calculate Others
#######################################################################################
tcatch <- rowSums(kusko.data[substr(names(kusko.data),1,2)=='H.'],dims = 1,na.rm=T)
# Extract escapement data
esc <- kusko.data[substr(names(kusko.data),1,2)=='w.'|substr(names(kusko.data),1,2)=='a.']
t.esc <- kusko.data$In.river - tcatch
# Calculate observed minimum escapement
minesc <- rowSums(esc, na.rm=T, dims = 1)
# Calculate observed minimum run
minrun <- rowSums(cbind(tcatch,esc), na.rm=T, dims = 1)
ny <- length(kusko.data[,1])
#######################################################################################
# 2.4 Construct dataset used for likelihood modeling
#######################################################################################
kusko.like.data <- as.matrix(cbind(tcatch,inr,esc,testf[3:8],ccat,ceff,creg))
```

```
nb.likelihood <- function(theta,likedat,ny){
### Total run  ####################################################################
	totrun <- exp(theta[1:ny])
### Weir slope parameters ##########################################################
	w.kwe <- exp(theta[ny+1])
	w.tul <- exp(theta[ny+2])
	w.geo <- exp(theta[ny+3])
	w.kog <- exp(theta[ny+4])
	w.tat <- exp(theta[ny+5])
	w.tak <- exp(theta[ny+6])
### Aerial slope parameters ########################################################
	a.kwe <- exp(theta[ny+7])
	a.kis <- exp(theta[ny+8])
	a.tul <- exp(theta[ny+9])
	a.sla <- exp(theta[ny+10])
	a.kip <- exp(theta[ny+11])
	a.ank <- exp(theta[ny+12])
	a.hlk <- exp(theta[ny+13])
	a.osk <- exp(theta[ny+14])
	a.hlt <- exp(theta[ny+15])
	a.che <- exp(theta[ny+16])
	a.gag <- exp(theta[ny+17])
	a.pit <- exp(theta[ny+18])
	a.ber <- exp(theta[ny+19])
	a.slp <- exp(theta[ny+20])

### Catch coefficient parameters ###################################################
# catchability coefficient Unrestricted
	q1 <- exp(theta[ny+21])
# catchability coefficient Restricted
	q2 <- exp(theta[ny+22])
# catchability coefficient Center Core monofilament
```

```
	q3 <- exp(theta[ny+23])
### Overdispersion parameters, weirs ############################################
	r.kwe <- exp(theta[ny+24])
	r.tul <- exp(theta[ny+25])
	r.geo <- exp(theta[ny+26])
	r.kog <- exp(theta[ny+27])
	r.tat <- exp(theta[ny+28])
	r.tak <- exp(theta[ny+29])
### Overdispersion parameters, aerial ############################################
	ra.kwe <- exp(theta[ny+30])
	ra.kis <- exp(theta[ny+31])
	ra.tul <- exp(theta[ny+32])
	ra.sla <- exp(theta[ny+33])
	ra.kip <- exp(theta[ny+34])
	ra.ank <- exp(theta[ny+35])
	ra.hlk <- exp(theta[ny+36])
	ra.osk <- exp(theta[ny+37])
	ra.hlt <- exp(theta[ny+38])
	ra.che <- exp(theta[ny+39])
	ra.gag <- exp(theta[ny+40])
	ra.pit <- exp(theta[ny+41])
	ra.ber <- exp(theta[ny+42])
	ra.slp <- exp(theta[ny+43])
### Likelihood model ##########################################################
	tfw  <-  rep(0,6)
	tfa  <-  rep(0,14)
	tft  <-  0
	tfc  <-  0
	esc  <-  totrun-likedat[,1]
#### Definie the negative binomial function ########################################
	nblike <- function(obs,r,est){
	lgamma(obs+r)-lgamma(obs+1)-lgamma(r)+r*log(r/(est+r))+obs*log(est/(est+r))
	}
```

```
#### Weir likelihood ##############################################################
        tfw[1]  <-  -sum(nblike(likedat[,5],r.kwe,esc/w.kwe),na.rm=T)
        tfw[2]  <-  -sum(nblike(likedat[,6],r.tul,esc/w.tul),na.rm=T)
        tfw[3]  <-  -sum(nblike(likedat[,7],r.geo,esc/w.geo),na.rm=T)
         tfw[4]  <-  -sum(nblike(likedat[,8],r.kog,esc/w.kog),na.rm=T)
         tfw[5]  <-  -sum(nblike(likedat[,9],r.tat,esc/w.tat),na.rm=T)
        tfw[6]  <-  -sum(nblike(likedat[,10],r.tak,esc/w.tak),na.rm=T)
#### Aerial likelihood ##############################################################
        tfa[1]  <-  -sum(nblike(likedat[,11],ra.kwe,esc/a.kwe),na.rm=T)
         tfa[2]  <-  -sum(nblike(likedat[,12],ra.kis,esc/a.kis),na.rm=T)
         tfa[3]  <-  -sum(nblike(likedat[,13],ra.tul,esc/a.tul),na.rm=T)
         tfa[4]  <-  -sum(nblike(likedat[,14],ra.sla,esc/a.sla),na.rm=T)
        tfa[5]  <-  -sum(nblike(likedat[,15],ra.kip,esc/a.kip),na.rm=T)
         tfa[6]  <-  -sum(nblike(likedat[,16],ra.ank,esc/a.ank),na.rm=T)
         tfa[7]  <-  -sum(nblike(likedat[,17],ra.hlk,esc/a.hlk),na.rm=T)
         tfa[8]  <-  -sum(nblike(likedat[,18],ra.osk,esc/a.osk),na.rm=T)
         tfa[9]  <-  -sum(nblike(likedat[,19],ra.hlt,esc/a.hlt),na.rm=T)
         tfa[10]  <-  -sum(nblike(likedat[,20],ra.che,esc/a.che),na.rm=T)
         tfa[11]  <-  -sum(nblike(likedat[,21],ra.gag,esc/a.gag),na.rm=T)
         tfa[12]  <-  -sum(nblike(likedat[,22],ra.pit,esc/a.pit),na.rm=T)
         tfa[13]  <-  -sum(nblike(likedat[,23],ra.ber,esc/a.ber),na.rm=T)
        tfa[14]  <-  -sum(nblike(likedat[,24],ra.slp,esc/a.slp),na.rm=T)
#### Inriver normal likelihood ########################################################
        tft  <-  0.5*sum((likedat[,2]-totrun)^2/(likedat[,3])^2,na.rm=T)
#### Weekly Catch likelihood, calculated estimated run by week ########################
        wk.est <- likedat[,25:30]*totrun
#### Calculate likelihoood for unrestricted#############################################
# Extract all mesh regulation year/week
        unr <- likedat[,43:48]
# Keep unrestricted mesh regulation year/week 1: indicate unrestricted period
        unr[unr != 1] <- NA
# Observed Effort
# Keep only Effort of Unrestricted
```

```
	unr.eff <- likedat[,37:42]*unr
# Rmove all NA
	unr.eff <- unr.eff[!is.na(unr.eff)]
# Observed harvest
# Keep only Effort of Unrestricted
	unr.h <- likedat[,31:36]*unr
# Rmove all NA
	unr.h <- unr.h[!is.na(unr.h)]
# Estimated
# Keep only Effort of Unrestricted
	unr.wk <- wk.est*unr
# Rmove all NA
	unr.wk <- unr.wk[!is.na(unr.wk)]
# likelihood for Unrestricted
   tf1 <- 0.5*length(unr.eff)*log(sum((log(unr.eff)-log(-log(1-unr.h/unr.wk)/q1))^2,na.rm=T))

#### Calculate likelihood for restricted ##################################################
# Extract restricted mesh period
# Extract all mesh regulation year/week
	r <- likedat[,43:48]
# Keep unrestricted mesh regulation year/week 2: indicate restricted periods
	r[r != 2] <- NA
# Change it to 1
	r[r == 2] <- 1
# Observed effort
# Keep only Effort of Restricted
	r.eff <- likedat[,37:42]*r
# Rmove all NA
	r.eff <- r.eff[!is.na(r.eff)]
# Observed harvest
# Keep only Effort of Restricted
	r.h <- likedat[,31:36]*r
# Rmove all NA
```

```
        r.h <- r.h[!is.na(r.h)]
# Estimated
# Keep only Effort of Unrestricted
        r.wk <- wk.est*r
# Rmove all NA
        r.wk <- r.wk[!is.na(r.wk)]
# likelihood for Unrestricted
  tf2 <- 0.5*length(r.eff)*log(sum((log(r.eff)-log(-log(1-r.h/r.wk)/q2))^2,na.rm=T))
#### Calculate likelihood for Monofilament############################################
# Extract Monfilament periods
# Extract all mesh regulation year/week (This is taking only 3-6 weeks
        m <- likedat[,43:48]
# Keep monofilament mesh regulation year/week 3: indicate monofilament peiriods
        m[(m != 3)&(m != 5)] <- NA
# Change it to 1
        m[!is.na(m)] <- 1
# Observed effort
# Keep only Effort of Restricted
        m.eff <- likedat[,37:42]*m
# Rmove all NA
        m.eff <- m.eff[!is.na(m.eff)]
# Observed harvest
# Keep only Effort of Restricted
        m.h <- likedat[,31:36]*m
# Rmove all NA
        m.h <- m.h[!is.na(m.h)]
# Estimated
# Keep only Effort of Restricted
        m.wk <- wk.est*m
# Rmove all NA
        m.wk <- m.wk[!is.na(m.wk)]
```

```
  tf3 <- 0.5*length(m.eff)*log(sum((log(m.eff)-log(-log(1-
ifelse(m.h/m.wk<1,m.h/m.wk,0.999))/q3))^2,na.rm=T))
tfc <-sum(tf1,tf2,tf3)

#### Likelihood calculation ############################################################
loglink  <- sum(sum(tfw),sum(tfa),tft,tfc,na.rm=T)
return(loglink)
}
#### 3.1 Set Initial value and boundaries ##############################################
# Initial starting point
        init <- c(rep(log(250000),ny),rep(5,6),rep(4,14),rep(-10,3),rep(2,6),rep(2,14))
# Lower bounds
        lb <-  c(log(minrun),rep(2,6), rep(3,14),rep(-14,3),rep(-3,6),rep(-3,14))
# Upper bounds
        ub <-  c(rep(log(500000),ny),rep(7,6),rep(8,14),rep(-5,3),rep(5,6),rep(5,14))
#### 3.3 Run likelihood model##########################################################
ptm <- proc.time()
nll  <-  optim(par=init,fn=nb.likelihood,method="L-BFGS-B",lower=lb,  upper  =  ub,  control  =
list(maxit=1000),likedat=kusko.like.data, ny=ny, hessian = T)
min_NLL <- nll$value
proc.time() - ptm
nll$convergence
Rprof()
nll$par
nll$value
#### 3.4  Calculate Wald Confidence Interval ###########################################
#1: Hessian Matrix
        hessian_obs <- nll$hessian
        log_est_obs <- nll$par
        est_obs <- exp(log_est_obs)
# Create a variance-covariance matrix
        var_covar_mat_obs <- solve(hessian_obs)
# Pull out diagonal
```

```
	log_var_obs <- diag(var_covar_mat_obs)
# Calculate standard error
	log_std_err_obs <- sqrt(log_var_obs)
	upper95CI <- exp(log_est_obs + 1.96*log_std_err_obs)
	lower95CI <- exp(log_est_obs - 1.96*log_std_err_obs)
	labelT <- length(ny)

for (i in 1:ny){
labelT[i] <- paste('Run',1975+i)
}
labelT <- c(labelT,names(esc),'q1','q2','q3',names(esc))
output <-
data.frame(parameter=labelT,mean=exp(nll$par),lower95CI=lower95CI,lower95CI=upper95CI)
```

APPENDIX B: MODEL INPUT DATA

Appendix B1.–Independent estimates of Kuskokwim River Chinook salmon abundance, used to scale the run reconstruction model.

Var name:	Year	In.river	In.river.sd
Conventional name:	Year	Total Run	Standard Error
	2003	241,617	36,605
	2004	422,657	71,241
	2005	345,814	46,672
	2006	396,248	62,850
	2007	266,219	32,950

Appendix B2.–Harvest of Kuskokwim River Chinook salmon.

Var name:	Year	H.Com	H.Sub	H.Sports	H.Test
Conventional name:	Year	Commercial	Subsistence	Sport	Test fish
	1976	30,735	58,606		1,206
	1977	35,830	56,580	33	1,264
	1978	45,641	36,270	116	1,445
	1979	38,966	56,283	74	979
	1980	35,881	59,892	162	1,033
	1981	47,663	61,329	189	1,218
	1982	48,234	58,018	207	542
	1983	33,174	47,412	420	1,139
	1984	31,742	56,930	273	231
	1985	37,889	43,874	85	79
	1986	19,414	51,019	49	130
	1987	36,179	67,325	355	384
	1988	55,716	70,943	528	576
	1989	43,217	81,175	1,218	543
	1990	53,502	109,778	394	512
	1991	37,778	74,820	401	149
	1992	46,872	82,654	367	1,380
	1993	8,735	87,674	587	2,515
	1994	16,211	103,343	1,139	1,937
	1995	30,846	102,110	541	1,421
	1996	7,419	96,413	1,432	247
	1997	10,441	79,381	1,227	332
	1998	17,359	81,213	1,434	210
	1999	4,705	72,775	252	98
	2000	444	67,620	105	64
	2001	90	78,009	290	86
	2002	72	80,982	319	288
	2003	158	67,134	401	409
	2004	2,305	96,788	857	691
	2005	4,784	85,090	572	557
	2006	2,777	90,085	444	352
	2007	179	96,155	1,478	305
	2008	8,865	98,103	708	420
	2009	6,664	78,231	904	470
	2010	2,732	66,056	354	292
	2011	747	62,368	579	337
	2012	627	22,544	0	321
	2013	174	47,113	0	201
	2014	35	11,203	0	497
	2015	8	16,111	0	472
	2016	0	30,676	0	522

Appendix B3.–Weir escapement counts of Kuskokwim River Chinook salmon.

Var name:	Year	w.kwe	w.tul	w.geo	w.kog	w.tat	w.tak
Conventional name:	Year	Kwethluk	Tuluksak	George	Kogrukluk	Tatlawiksuk	Takotna
	1976				5,638		
	1977						
	1978				14,533		
	1979				11,393		
	1980						
	1981				16,089		
	1982				13,126		
	1983						
	1984				4,922		
	1985				4,442		
	1986						
	1987						
	1988				8,028		
	1989						
	1990				10,093		
	1991		697		6,835		
	1992	9,675	1,083		6,563		
	1993		2,218		12,377		
	1994		2,918				
	1995				20,662		
	1996			7,770	13,771		423
	1997			7,810	13,190		1,197
	1998						
	1999				5,543	1,484	
	2000	3,547		2,959	3,242	807	345
	2001		997	3,277	7,475	1,978	718
	2002	8,502	1,346	2,443	10,025	2,237	316
	2003	14,474	1,064		12,008		390
	2004	28,605	1,475	5,488	19,819	2,833	461
	2005		2,653	3,845	21,819	2,864	499
	2006	17,619	1,043	4,355	20,205	1,700	541
	2007	12,927	374	4,011		2,032	412
	2008	5,276	701	2,563	9,750	1,075	413
	2009	5,744	362	3,663	9,528	1,071	311
	2010	1,667	201	1,498	5,812	546	181
	2011	4,079	284	1,547	6,731	992	136
	2012		555	2,201		1,116	228
	2013	845	193	1,292	1,819	495	97
	2014	3,187	320	2,993	3,732	1,904	
	2015	8,162	709	2,282	8,081	2,104	
	2016	7,619	909	1,663	7,056	2,494	

Appendix B4.–Peak aerial survey index counts of Kuskokwim River Chinook salmon.

Var name:	Year	a.kwe	a.kis	a.tul	a.sla	a.kip	a.ank	a.hlk	a.osk	a.hlt	a.che	a.gag	a.pit	a.ber	a.slp
Conventional name:	Year	Kwethluk	Kisaralik	Tuluksak	Salmon (Aniak)	Kipchuk	Aniak	Holokuk	Oskawalik	Holitna	Cheeneetnuk	Gagaryah	Pitka	Bear	Salmon(Pitka)
	1976									2,571				182	
	1977	2,075		424							2,407	897			1,930
	1978	1,722	2,417		289					2,766	268	504		227	1,100
	1979														682
	1980			975	1,186										
	1981						9,074							93	
	1982		81		126					521				127	413
	1983	471		186	231		1,909			1,069	173				572
	1984										1,177				545
	1985		63	142							1,002				620
	1986				336		424			650					
	1987				516	193			193		317				
	1988	622	869	195	244		954		80						474
	1989	1,157	152		631	1,598	2,109								452
	1990		631	200	596	537	1,255		113						
	1991		217	358	583	885	1,564								
	1992				335	670	2,284		91	2,022	1,050	328			2,536
	1993				1,082	1,248	2,687	233	103	1,573	678	419			1,010
	1994		1,243		1,218	1,520					1,206	807			1,010
	1995		1,243		1,446	1,215	3,171		326	1,887	1,565	1,193			1,911
	1996				985										
	1997		439		980	855	2,187		1,470	2,093	345	364			
	1998		457		425	443	1,930								
	1999								98	741					
	2000				238	182	714			301			151		362
	2001				598			52		4,156		143		175	1,033
	2002	1,795	1,727		1,236	1,615		513	295	733	730		165	211	
	2003	2,661	654	94	1,242	1,493	3,514	1,096	844		810	1,093	197	176	
	2004	6,801	5,157	1,196	2,177	1,868	5,362	539	293	4,051	918	670	290	206	1,138

-continued-

Appendix B4.–Page 2 of 2.

Var name	Year	a.kwe	a.kis	a.tul	a.sla	a.kip	a.ank	a.hlk	a.osk	a.hlt	a.che	a.gag	a.pit	a.ber	a.slp
Conventional name	Year	Kwethluk	Kisaralik	Tuluksak	Salmon (Aniak)	Kipchuk	Aniak	Holokuk	Oskawalik	Holitna	Cheeneetnuk	Gagaryah	Pitka	Bear	Salmon(Pitka)
	2005	5,059	2,206	672	4,097	1,679		510	582	1,760			744	367	1,801
	2006		4,734			1,618	5,639	705	386	1,866	1,015	531	170	347	862
	2007		692	173	1,458	2,147	3,984					1,035	131	165	943
	2008	487	1,074		589	1,061	3,222	418	213		290	177	248	245	1,033
	2009							565	379		323	303	187	209	632
	2010		235					229				62	67	75	135
	2011				79	116		61	26		249	96	85	145	767
	2012		588		49	193		36	51		229	178			670
	2013	1,165	599	83	154	261	754		38	532	138	74		64	469
	2014		622		497	1,220	3,201	80	200		340	359			1,865
	2015		709		810	917		77		662					2,016
	2016		622			898	718	100	47	1,157	217	135		580	1,578

Note: Only surveys rated “good” or “fair” were used. Only surveys flown between July 17 and August 5, inclusive, were used. Chinook salmon live and carcass counts were combined.

Appendix B5.–Proportion of total annual Chinook salmon run in District W-1 by week, as estimated by Bethel test fishery.

Var name:	Year	rpw.3	rpw.4	rpw.5
Conventional name:	Year	6/10–6/16	6/17–6/23	6/24–6/30
	1976			
	1977			
	1978			
	1979			
	1980			
	1981			
	1982			
	1983			
	1984	0.2243	0.2903	0.1488
	1985	0.0000	0.0930	0.2427
	1986	0.1503	0.4039	0.1656
	1987	0.1988	0.3070	0.2368
	1988	0.2080	0.3086	0.1786
	1989	0.1769	0.2780	0.3474
	1990	0.1434	0.2095	0.3325
	1991	0.0593	0.2965	0.2942
	1992	0.3466	0.1791	0.2132
	1993	0.2148	0.4172	0.1270
	1994	0.2883	0.3098	0.1396
	1995	0.1566	0.3066	0.3005
	1996	0.4007	0.2138	0.0963
	1997	0.1913	0.5295	0.1196
	1998	0.1166	0.2199	0.3866
	1999	0.1360	0.1349	0.2469
	2000	0.2089	0.3896	0.1530
	2001	0.0791	0.4157	0.2510
	2002	0.3547	0.2245	0.1601
	2003	0.2764	0.2748	0.1433
	2004	0.2130	0.2927	0.2513
	2005	0.2335	0.2851	0.1876
	2006	0.1299	0.3054	0.2935
	2007	0.0996	0.2000	0.3114
	2008	0.1524	0.2931	0.3057
	2009	0.1955	0.2830	0.3460
	2010	0.2190	0.3755	0.1517
	2011	0.1188	0.2976	0.1996
	2012	0.0508	0.2964	0.3308
	2013	0.1681	0.3708	0.2654
	2014	0.2834	0.2370	0.1217
	2015	0.1859	0.2292	0.1520
	2016	0.1696	0.1830	0.2085

-continued-

		6	7	8	9	Post-9
Var name:	Year	rpw.6	rpw.7	rpw.8	rpw.9	rpw.10
Conventional name:	Year	7/1–7/7	7/8–7/14	7/15–7/21	7/22–7/28	7/29–8/26
	1976					
	1977					
	1978					
	1979					
	1980					
	1981					
	1982					
	1983					
	1984	0.1633	0.0509	0.0522	0.0090	0.0173
	1985	0.4306	0.1504	0.0247	0.0175	0.0410
	1986	0.1399	0.0488	0.0097	0.0241	0.0000
	1987	0.1137	0.0210	0.0344	0.0130	0.0094
	1988	0.0852	0.0218	0.0419	0.0145	0.0192
	1989	0.0976	0.0258	0.0190	0.0119	0.0112
	1990	0.1492	0.0609	0.0136	0.0266	0.0256
	1991	0.1994	0.0337	0.0430	0.0000	0.0000
	1992	0.1085	0.0542	0.0554	0.0000	0.0118
	1993	0.0328	0.0273	0.0097	0.0000	0.0000
	1994	0.1009	0.0138	0.0122	0.0000	0.0061
	1995	0.0988	0.0300	0.0050	0.0097	0.0050
	1996	0.0288	0.0214	0.0000	0.0066	0.0033
	1997	0.0533	0.0357	0.0119	0.0079	0.0059
	1998	0.1513	0.0378	0.0116	0.0055	0.0000
	1999	0.1462	0.1903	0.0297	0.0754	0.0297
	2000	0.0461	0.0205	0.0410	0.0000	0.0183
	2001	0.1036	0.0528	0.0367	0.0000	0.0156
	2002	0.1034	0.0337	0.0137	0.0089	0.0132
	2003	0.0662	0.0351	0.0255	0.0112	0.0042
	2004	0.0693	0.0406	0.0537	0.0160	0.0021
	2005	0.1601	0.0768	0.0062	0.0000	0.0168
	2006	0.1675	0.0535	0.0114	0.0142	0.0105
	2007	0.2472	0.0754	0.0316	0.0095	0.0032
	2008	0.1183	0.0431	0.0334	0.0083	0.0139
	2009	0.0753	0.0323	0.0164	0.0000	0.0049
	2010	0.1335	0.0556	0.0185	0.0113	0.0103
	2011	0.1695	0.0818	0.0130	0.0000	0.0031
	2012	0.2114	0.0627	0.0201	0.0088	0.0127
	2013	0.0963	0.0743	0.0108	0.0000	0.0000
	2014	0.0771	0.0148	0.0146	0.0000	0.0029
	2015	0.1316	0.0625	0.0591	0.0338	0.0238
	2016	0.1385	0.0722	0.0296	0.0197	0.0112

Appendix B6.–Chinook Salmon catch and effort (permit-hours) by week for Kuskokwim River District W-1

		Week 3 6/10–6/16			Week 4 6/17–6/23		
Var name:	Year	chw.3	cew.3	cfw.3	chw.4	cew.4	cfw.4
Conventional name:	Year	Catch	Effort	Net	Catch	Effort	Net
	1976	0	0	0	20,010	5,724	1
	1977	12,458	2,802	1	16,227	2,904	1
	1978	18,483	3,972	1	10,066	2,004	1
	1979	24,633	6,432	1	5,651	3,012	2
	1980	9,891	2,814	1	21,698	5,364	4
	1981	29,882	6,180	1	3,830	3,066	2
	1982	4,912	2,784	1	24,628	5,970	1
	1983	13,406	5,634	1	8,063	5,544	2
	1984	0	0	0	17,181	5,562	1
	1985	0	0	0	6,519	2,538	3
	1986	0	0	0	0	0	0
	1987	0	0	0	19,126	4,734	3
	1988	12,640	4,816	3	11,708	3,672	3
	1989	0	0	0	15,215	5,208	3
	1990	0	0	0	16,690	3,780	3
	1991	0	0	0	13,813	3,606	3
	1992	0	0	0	24,334	9,488	3
	1993	0	0	0	0	0	0
	1994	0	0	0	0	0	0
	1995	0	0	0	6,895	2,276	3
	1996	0	0	0	4,091	1,056	3
	1997	0	0	0	10,023	2,118	3
	1998	0	0	0	0	0	0
	1999	0	0	0	0	0	0
	2000	0	0	0	0	0	0
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	0	0	0	0	0	0
	2005	0	0	0	0	0	0
	2006	0	0	0	0	0	0
	2007	0	0	0	0	0	0
	2008	0	0	0	6,415	1,026	3
	2009	0	0	0	3,003	668	3
	2010	0	0	0	0	0	0
	2011	0	0	0	0	0	0
	2012	0	0	0	0	0	0
	2013	0	0	0	0	0	0
	2014	0	0	0	0	0	0
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0

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		Week 5 6/24–6/30			Week 6 7/1–7/7		
Var name:	Year	chw.5	cew.5	cfw.5	chw.6	cew.6	cfw.6
Conventional name:	Year	Catch	Effort	Net	Catch	Effort	Net
	1976	4,143	2,088	2	1,550	2,490	2
	1977	1,841	4,722	2	673	4,194	2
	1978	3,723	5,346	2	2,354	8,676	2
	1979	3,860	6,438	2	1,233	3,252	2
	1980	1,460	2,448	2	498	2,298	2
	1981	4,563	5,952	2	2,795	5,520	2
	1982	12,555	5,176	4	1,970	3,968	2
	1983	4,925	5,958	2	2,415	5,634	2
	1984	5,643	5,616	2	3,206	5,454	2
	1985	19,204	5,880	3	9,942	5,844	3
	1986	11,986	6,540	3	5,029	6,852	3
	1987	0	0	0	9,606	6,948	3
	1988	15,060	7,518	3	5,871	6,954	3
	1989	11,094	6,144	3	7,911	7,092	3
	1990	25,459	7,536	3	4,071	3,546	3
	1991	12,612	3,696	3	8,068	7,308	3
	1992	16,307	8,628	3	3,250	4,696	3
	1993	8,184	4,976	3	0	0	0
	1994	14,221	4,608	3	0	0	0
	1995	14,424	4,532	3	4,368	3,824	3
	1996	666	360	3	861	836	3
	1997	0	0	0	0	0	0
	1998	12,771	4,584	3	2,277	1,780	3
	1999	4,668	2,454	3	0	0	0
	2000	0	0	0	357	896	3
	2001	0	0	0	0	0	0
	2002	0	0	0	0	0	0
	2003	0	0	0	0	0	0
	2004	520	104	3	1,107	446	3
	2005	3,531	1,189	3	874	604	3
	2006	2,493	1,038	3	0	0	0
	2007	0	0	0	0	0	0
	2008	2,362	783	3	19	4	3
	2009	2,539	752	3	762	519	3
	2010	1,724	1,324	5	290	522	3
	2011	0	0	0	361	634	5
	2012	0	0	0	0	0	0
	2013	0	0	0	0	0	0
	2014	0	0	0	0	0	0
	2015	0	0	0	0	0	0
	2016	0	0	0	0	0	0

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		Week 7 7/8–7/14			Week 8 7/15–7/21			Week 9 7/22–7/28		
Var name:	Year	chw.7	cew.7	cfw.7	chw.8	cew.8	cfw.8	chw.9	cew.9	cfw.9
Conventional name:	Year	Catch	Effort	Net	Catch	Effort	Net	Catch	Effort	Net
	1976	1,238	4,548	2	236	1,590	2	0	0	0
	1977	153	2,310	2	0	0	0	0	0	0
	1978	987	7,668	2	0	0	0	0	0	0
	1979	470	3,120	2	0	0	0	0	0	0
	1980	445	2,586	2	0	0	0	0	0	0
	1981	941	2,640	2	0	0	0	0	0	0
	1982	1,055	4,734	2	0	0	0	0	0	0
	1983	633	2,796	2	0	0	0	0	0	0
	1984	2,069	5,592	2	744	2,238	2	0	0	0
	1985	0	0	0	0	0	0	0	0	0
	1986	1,156	3,192	3	0	0	0	0	0	0
	1987	1,910	3,582	3	2,758	6,720	3	0	0	0
	1988	5,270	10,794	3	1,728	6,636	3	662	6,276	3
	1989	6,043	10,962	3	868	2,622	3	210	3,372	3
	1990	4,931	8,534	3	0	0	0	0	0	0
	1991	904	3,426	3	452	3,408	3	419	7,522	3
	1992	0	0	0	0	0	0	0	0	0
	1993	0	0	0	0	0	0	0	0	0
	1994	578	1,984	3	441	3,000	3	538	6,348	3
	1995	1,452	3,716	3	568	3,488	3	0	0	0
	1996	408	896	3	251	1,195	3	307	6,398	3
	1997	0	0	0	0	0	0	0	0	0
	1998	1,127	1,668	3	0	0	0	816	4,296	3
	1999	0	0	0	0	0	0	0	0	0
	2000	0	0	0	0	0	0	0	0	0
	2001	0	0	0	0	0	0	0	0	0
	2002	0	0	0	0	0	0	0	0	0
	2003	0	0	0	0	0	0	0	0	0
	2004	0	0	0	0	0	0	127	360	3
	2005	0	0	0	0	0	0	0	0	0
	2006	0	0	0	0	0	0	0	0	0
	2007	0	0	0	0	0	0	0	0	0
	2008	1	6	3	0	6	0	0	12	0
	2009	113	436	3	83	672	3	58	752	3
	2010	271	686	3	186	958	3	176	1,632	3
	2011	227	996	5	129	1,226	5	24	1,668	5
	2012	45	604	5	195	1,616	5	39	1,464	5
	2013	0	0	0	139	2,018	5	21	1,556	5
	2014	14	584	5	14	2,276	5	0	0	0
	2015	0	0	0	0	0	0	0	0	0
	2016	0	0	0	0	0	0	0	0	0

Key to column Net:

1 = Gillnet mesh size unrestricted.
2 = Gillnets were restricted to 6.0 inch or less - old gear.
3 = Gillnets were restricted to 6.0 inch or less - new gear.
4 = Both unrestricted and restricted mesh size periods in the week.
5 = Personal use harvest also included in Catch and Effort calculations of 6.0 inch or less new gear.